# Coherent Resonant Soft X-Ray Magnetic Scattering

## Truth from speckle
## How magnets forget

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How can we determine precisely what the ensemble of nanoscopic magnetic domains is doing during static and dynamic magnetic hysteresis in the presence of disorder?

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# MY COWORKERS:

| | | |
|---|---|---|
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| Phillip Geissbuhler | | |
| Steve Kevan | | University of Oregon |
| Josh Turner | | |
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| Karine Chesnel | | |
| Eric Fullerton | | IBM Almaden |
| Olav Hellwig | | |

All of these experiments were done using beamline 9.0.1 at the ALS.
Raw undulator x-rays!

# What is the Ideal Source for Coherent Soft X-Ray Experiments?

## Lessons from Lasers:
## 1) CW (continuous wave)
## 2) Modulation (knobs!)
## 3) Below damage threshold

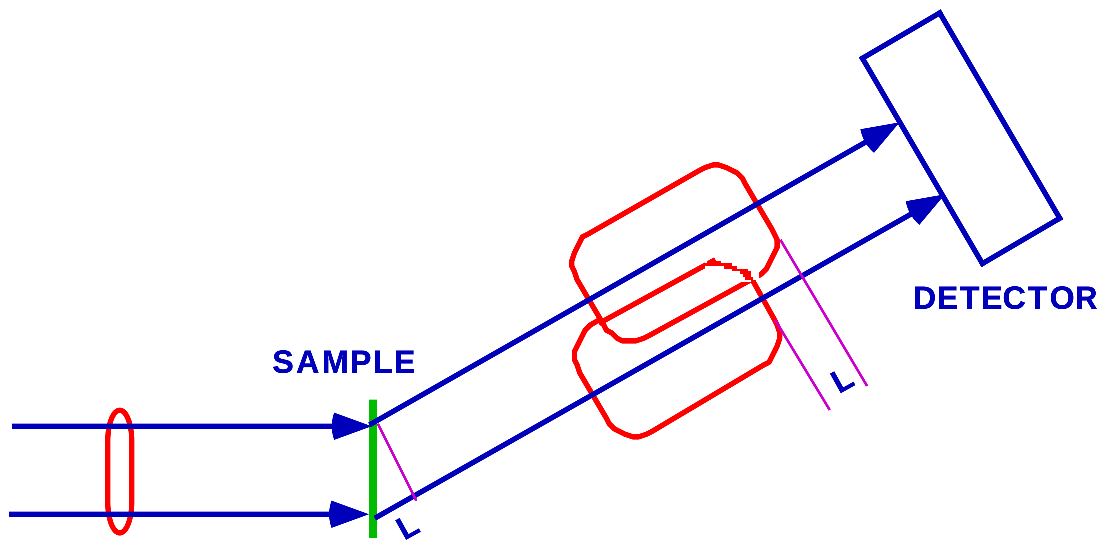
(1) Quasi-continuous beam is required to sample the thermal fluctuations efficiently. The proposed Stanford pulsed diffraction-limited undulator will be very bad for dynamic light scattering studies. No one has ever done dynamic light scattering with a pulsed laser.

Repetition rate 500 MHz to 500 GHz

(2) Variable bandwidth---from 10-2 to 10-5---is required to provide the optimum longitudinal coherence length for different dynamic light scattering experiments.

The narrow bandwidth beams from such a machine will have complete transverse coherence, and the longitudinal coherence necessary to do dynamic light scattering studies without damaging the samples---again, this is in sharp contrast to the proposed Stanford source.

# COMPARE WITH LASER SPECKLE




## LASER SPECKLE

| | |
|---|---|
| Coherent flux in | $10^{16}$ photons/second |
| Wavelength λ | 5320 Angstroms |
| Transverse correlation length | 2 mm (4,000λ) |
| Longitudinal correlation length | 10 cm (200,000λ) |

## UNDULATOR SPECKLE

| | |
|---|---|
| Coherent flux in | $10^{12}$ photons/second |
| Wavelength λ | 16 Angstroms |
| Transverse correlation length | 30 microns (19,000λ) |
| Longitudinal correlation length | 640 Angstroms (40λ) |
| | |
| Scattered flux out | $10^{6}$ to $10^{7}$ photons/second |
| Transverse correlation length | 30 microns (19,000λ) |
| Longitudinal correlation length | 25,600 Angstroms (1600λ) |
| Average size of magnetic domains | 2,000 Angstroms |
| Number of magnetic domains | 40,000 |

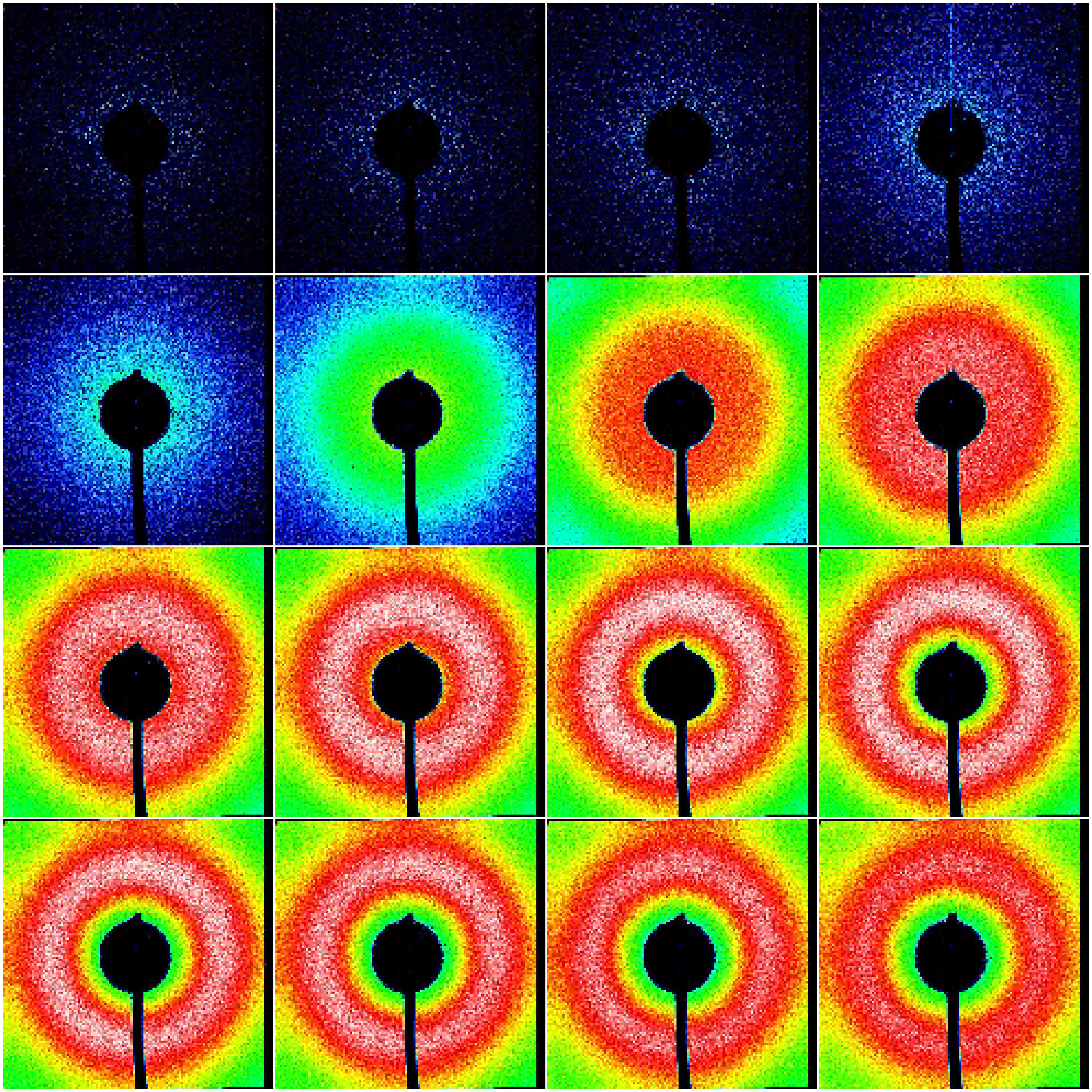
# DIFFERENT APPELLATIONS FOR DYNAMIC LIGHT SCATTERING

CXRD: coherent x-ray diffraction (CXD)
DLS: dynamic light scattering (SXDLS, XDLS)
FPI: Fabry-Perot Interferometry
IFS: intensity fluctuation spectroscopy (XIFS)
II: intensity interferometry
HBTI: Hanbury-Brown Twiss interferometry
HES: heterodyne spectroscopy
HOS: homodyne spectroscopy
LBS: light beating spectroscopy
OBS: optical beating spectroscopy
PCS: photon correlation spectroscopy (XPCS)
PDII: post detection intensity interferometry
QELS: quasielastic light scattering

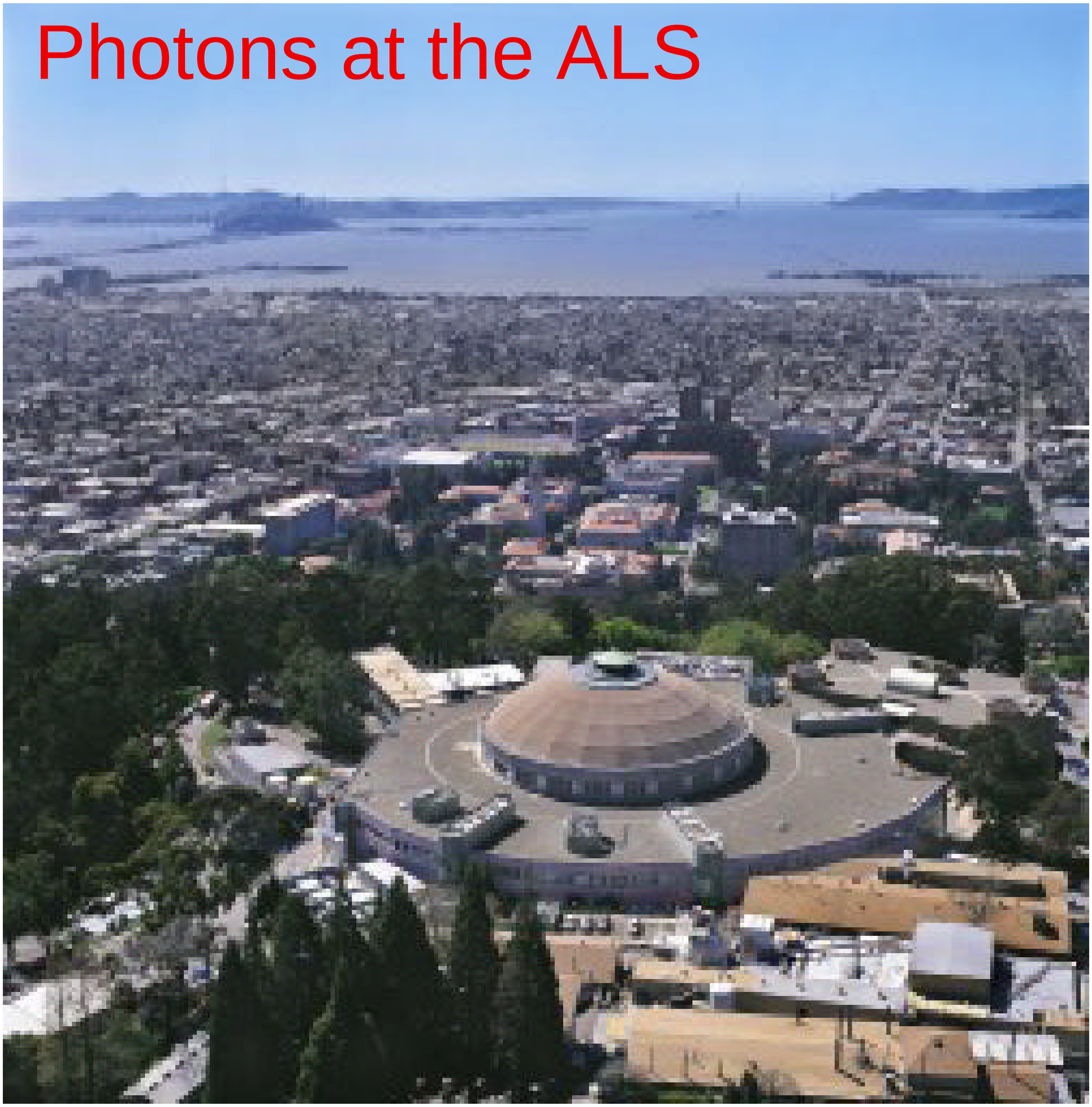
WORLD SPEED RECORDS:
Liquid crystal samples

1999  106 times faster
fast scintillator + PM
1 microsecond limit
3 microsecond times

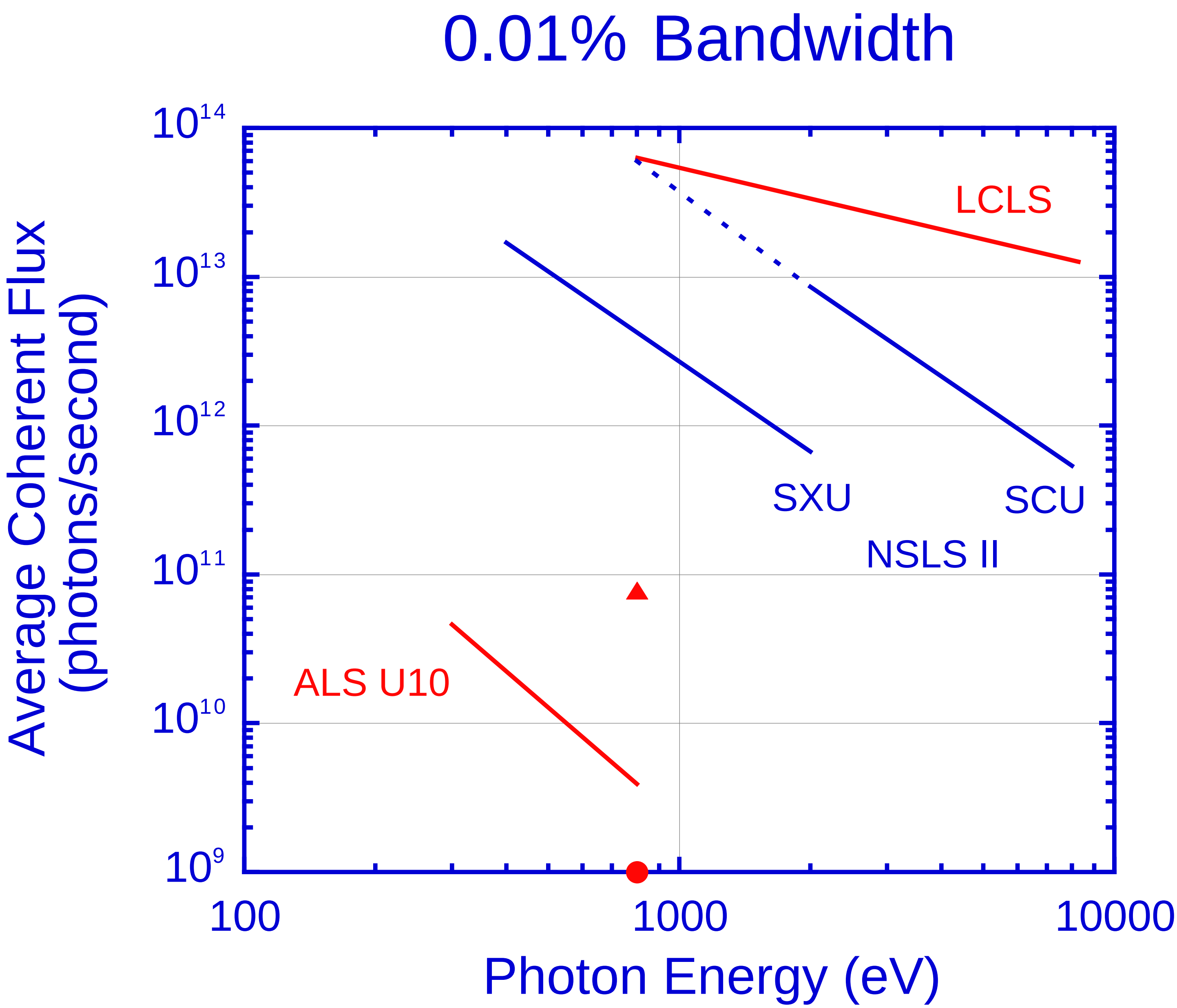
2003  20 times faster
avalanche photodiode
50 nanosecond limit
300 nanosecond times



Speckle Patterns versus Applied Magnetic Field




raw flux = 2 x $10^{14}$ photons/sec
coherent flux = 2 x $10^{12}$ photons/sec
scattered flux = 2 x $10^{7}$ photons/sec


0.01% Bandwidth
Average Coherent Flux
(photons/second)
10^14
10^13
10^12
10^11
10^10
10^9
LCLS
SXU
SCU
NSLS II
ALS U10
100
1000
10000
Photon Energy (eV)

COHERENT FLUX COMPARISON:

Proposed SXU

50 x ALS-2
damage threshold / 50

Theoretical SXU

770 x ALS-2
damage threshold / 3.3

Ultimate Ring

2600 x ALS-2
500 x PSXU NSLS-2
33 x TSXU NSLS-2

## RESOLUTION LIMITS:

| | |
|---|---|
| Proposed SXU | 1 microsec |
| Theoretical SXU | 30 nanosec |
| Ultimate Ring | 0.5 nanosec |

RECOMMENDATIONS:

1) Source Characteristics:
Quasi-CW and just below damage threshold

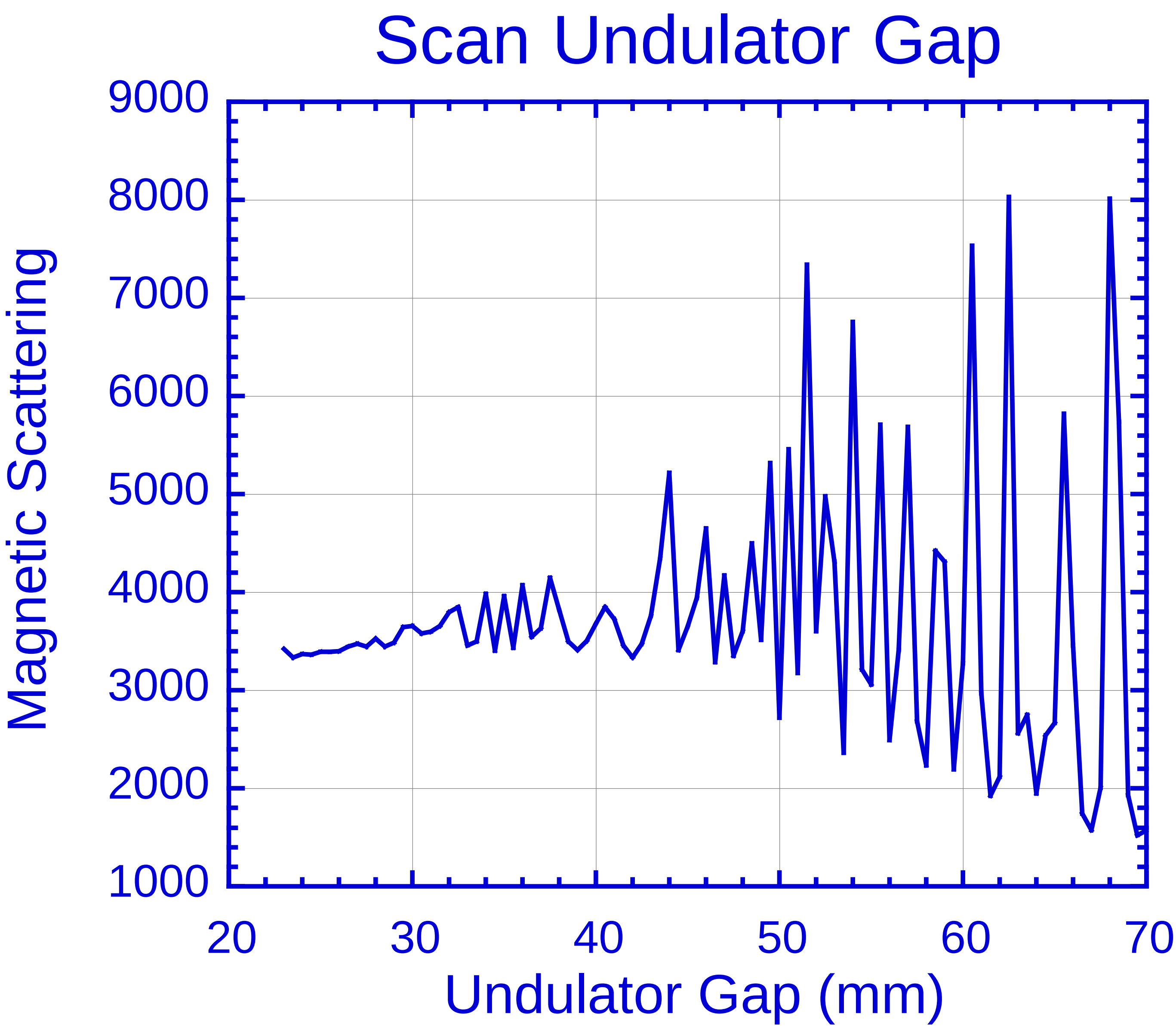
2) Photon Ecology:
Use all photon degrees of freedom:
a) Momentum
b) Energy
c) Polarization
d) Coherence
=> Fast modulation!

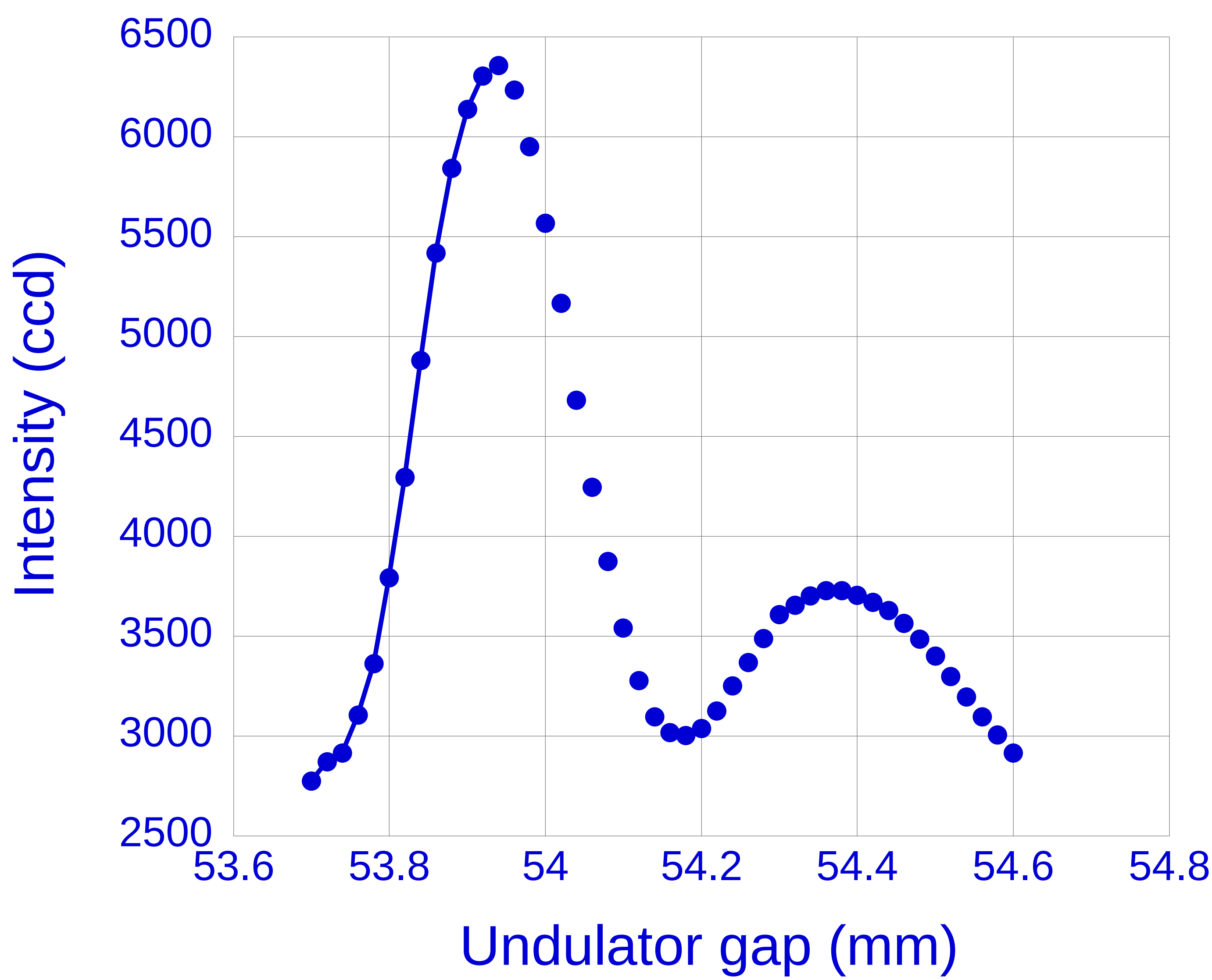
OPTICS:

Perfect Optics

No Optics

Just Right Optics


Scan Undulator Gap
9000
8000
7000
6000
5000
4000
3000
2000
1000
20
30
40
50
60
70
Undulator Gap (mm)
Magnetic Scattering


6500
6000
5500
5000
4500
4000
3500
3000
2500
Intensity (ccd)
53.6
53.8
54
54.2
54.4
54.6
54.8
Undulator gap (mm)

DETECTORS:

Perfect CCD

Fast Parallel

Associated Correlators

COHERENCE:

Perfect Coherence

versus

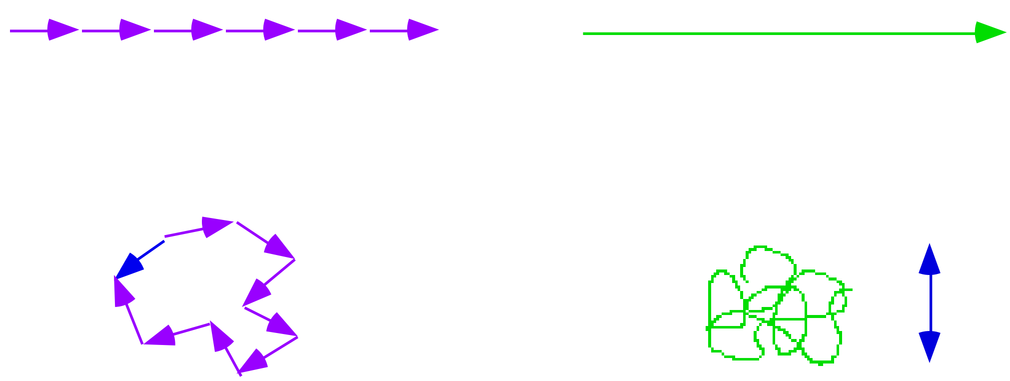
Partial Coherence

Want Variable Transverse
and Longitudinal Coherence!

# Magnetic Speckle

Coherent illumination of many (randomly located) magnetic domains => speckle pattern

Moving even a single magnetic domain produces large changes in the speckle pattern.



$E \propto N$

$I \propto N^2$

$E \propto \sqrt{\phantom{N}}$

$I \propto N$

By measuring these changes versus the applied magnetic field (history), we can determine the changes in the sample---both in time and space.

# MAGNETIC SPECKLE

Coherent x-rays => coherent illumination

Add up the scattering amplitudes from each magnetic domain.

Randomly positioned magnetic domains => speckle pattern

Moving even a single magnetic domain can produce a large change in the speckle pattern.

By measuring the changes in the speckle pattern, we can determine the changes in the sample---both in space and time.

# COHERENT SOFT X-RAY MAGNETIC SCATTERING

The magnetic domains in our sample act like many superimposed diffraction gratings. The photon scattering from these gratings produces our magnetic speckle patterns.

By measuring these magnetic speckle patterns, we can precisely determine very small changes in the magnetic domain arrangement.

Because our photon degeneracy parameter delta is very small, the interference takes place one photon at a time---our delta is only about $10^{-3}$.

Hanbury-Brown and Twiss first developed post detection intensity interferometry for optical and RF stellar interferometry.